UDC 551.557.31:551.510.534:551.547.3

A COMPARISON OF OBSERVED AND THEORETICAL DIURNAL TIDAL MOTIONS BETWEEN 30 AND 60 KILOMETERS[1]

RICHARD J. REED and MICHAEL J. OARD

Department of Atmospheric Sciences, University of Washington, Seattle, Wash.

and

MARYA SIEMINSKI[2]

ABSTRACT

Lindzen's theoretical predictions of the thermally driven diurnal tide are compared with observations of the diurnal amplitude and phase of the meridional wind component between 30 and 60 km for five groups of stations ranging in latitude from 64° N. to 8° S. In general, good agreement is found between theory and observation. The most important deviation occurs above 55 km where theoretical phases become progressively earlier than observed at lower latitude stations. This behavior suggests that the strength of the trapped modes in Lindzen's solutions is underestimated relative to that of the propagating modes. Since the trapped modes are driven primarily by ozone heating in the upper troposphere and lower mesosphere, it is suggested that the problem of ozone heating requires further examination.

1. INTRODUCTION

Meteorological rocket soundings have revealed the existence of diurnal tidal motions with amplitudes of several meters per second in the altitude range of 30–60 km (Miers, 1965; Beyers et al., 1966; Reed et al., 1966). These motions appear to have been successfully explained by Lindzen (1967) in his recent theory of the thermally driven diurnal tide. However, the data used by Lindzen in comparing his theoretical predictions to observations were too limited in number and too restricted geographically to permit an adequate comparison. The purpose of this paper is to present newly acquired statistics on diurnal tidal motions between 30 and 60 km that define the tidal characteristics more accurately over a wide range of latitudes and that provide a basis for making meaningful comparisons between theory and observation.

2. DATA AND ANALYSIS

The subsequent analysis is based on all published rocket wind data (Meteorological Rocket Network Committee, 1959–1963; Environmental Science Services Administration, 1964–1967) for June, July, and August through August 1966 for the first four groups of stations shown in table 1 and all published soundings, irrespective of month, through April 1967 for the single station, Ascension Island, in the fifth group. The beginning of record varies from station to station, dating back to June 1960 for about half of them. The number of soundings available for each group, at 2-hr intervals, is given in the table. Above 50 km the number progressively diminishes. Typically, about 30 percent of the soundings reach 60 km.

Comparisons of observed and theoretical results are made for the meridional wind component only. For the months selected for study at the various stations, this component is essentially free of synoptic variations and seasonal and other long-term trends that make it otherwise difficult to define the tidal motions accurately. Some success, however, has been achieved recently in determining the diurnal variation of the zonal component at White Sands and Cape Kennedy during summer when synoptic irregularities are absent and the seasonal trend is smooth and relatively easy to remove. The results of the zonal wind determinations will be presented separately in a later section.

The amplitude and phase of the diurnal cycle were determined at 1-km intervals by fitting diurnal and semidiurnal harmonics to the irregularity spaced data points by the methods of least squares. The time of observation for a data point was considered to be the launch time of the corresponding sounding in whole minutes, irrespective of altitude, and each data point was given equal weight in the analysis. The original analysis for group four (Barking Sands, Grand Turk, and Antigua) showed questionable values of the mean wind and semidiurnal component at higher levels where observations were scanty. Consequently, a reanalysis was made fitting diurnal harmonics only and assuming a zero mean (the value found for the other groups where the data are more satisfactory). This procedure produced diurnal amplitudes and phases that were more consistent with values from adjacent station groups.

The method of analysis described above consists, in effect, of fitting harmonic curves to hourly mean values that are weighted according to the number of observations in the hourly periods. The chosen weighting procedure forces the curves to adhere most closely to the most reliably determined mean values and appears to be the optimum procedure for the type of data being dealt with.

3. RESULTS

The amplitudes and phases, determined as described above, are shown in figures 1–5. Also depicted are theoretical amplitudes and phases for an isothermal atmosphere

[1] Contribution No. 196, Department of Atmospheric Sciences.
[2] Supported by National Science Foundation, Secondary Science Training Program.

TABLE 1.—*Number of observations*

Location		Local time											
		00–02	02–04	04–06	06–08	08–10	10–12	12–14	14–16	16–18	18–20	20–22	22–24
61° N.	Fort Greely, 64° N. Fort Churchill, 59° N.	6	2	5	2	27	138	33	13	5	7	5	5
37° N.	Green River, 39° N. Wallops Island, 38° N. Point Mugu, 34° N.	7	4	3	49	216	83	67	25	16	8	12	10
30° N.	White Sands, 32° N. Cape Kennedy, 28° N.	22	18	17	31	78	340	142	62	18	8	7	20
20° N.	Barking Sands, 22° N. Grand Turk, 21° N. Antigua, 17° N.	1	10	2	1	15	40	45	82	7	0	0	4
8° S.	Ascension Island, 8° S.	7	16	9	4	8	31	136	223	39	10	14	11

taken from a complete listing kindly supplied by Lindzen. Theoretical results for the standard tropical atmosphere were also supplied. These differed only slightly from the results for the isothermal atmosphere and are not presented here.

For the purpose of judging the reliability of the tidal determinations, the data were divided into two samples of equal size at each level, and harmonic analyses were carried out for each subgroup. The results of these analyses are indicated, for every second kilometer, at the end points of the bars plotted in figures 1–5. The two samples were formed by instructing the computer to put alternate observations from the total data sample for a particular station group and level into different categories. Usually but not always, the data were arranged in chronological order. In any event, whether chronologically arranged or not, the nature of the data is such that the two samples may be regarded as statistically independent. By and large, the differences in the independent determinations are small, lending confidence to the results. Since the amplitudes and phases for the total sample were determined separately and not as vector sums of the subgroup determinations, overall phases and amplitudes do not always lie between the values for the subgroups.

The comparisons for the different latitude groups will now be made:

61° N. (*Fort Greely, Fort Churchill*) At this latitude there is excellent agreement in both amplitude and phase between theory and observation. The observations show minor irregularities that may not be real. Above 55 km there is some indication that the observed amplitude is greater than the theoretical.

37° N. (*Green River, Wallops Island, Point Mugu*) Here there is broad agreement between theory and observation, but certain systematic differences begin to appear. The observed amplitude starts its increase at a higher level and reaches its peak at a lower level than the theoretical; hence, the increase in amplitude near 45 km is more rapid.

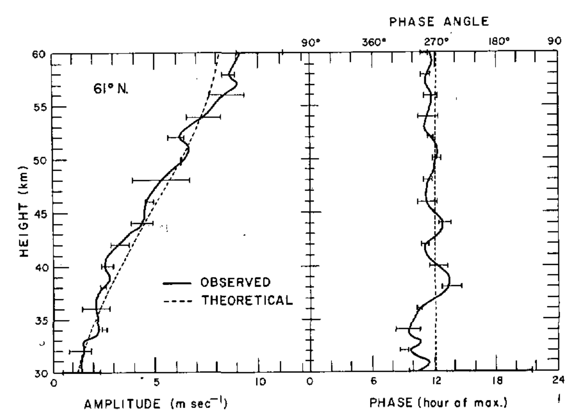

FIGURE 1.—Amplitude and phase of diurnal variation of meridional wind component at 61° N. The phase angle, in accordance with usual convention, gives the number of degrees in advance of origin (chosen as midnight) that the upcrossing of the sine curve occurs; maximum (max.).

At high levels the phase (in hours) is earlier in theory than in reality. At lower levels the profiles have the same shape but the latest time of maximum, 1500 LT both for theory and observation, occurs several kilometers lower in theory.

30° N. (*White Sands, Cape Kennedy*) At this latitude the differences noted for the preceding group become accentuated, though again there is quite good agreement in broad features. As before, the theoretical amplitude starts its increase too low and reaches its peak too high; moreover, the peak value is somewhat excessive. The theoretical phase is much too early at high levels. Below 40 km, the theoretical phase goes rapidly through a 360° change while the observed phase changes less markedly in the opposite sense.

20° N. (*Barking Sands, Grand Turk, Antigua*) Except that the observed amplitude appears to reach its peak at a somewhat higher level here than the theoretical, the remarks for the previous group apply. Below 40 km, the

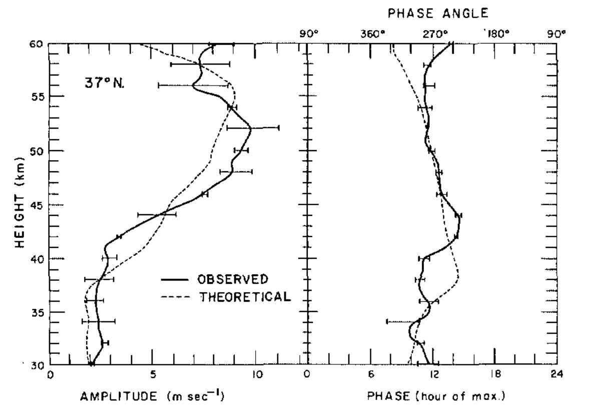

FIGURE 2.—Same as figure 1 for 37° N.

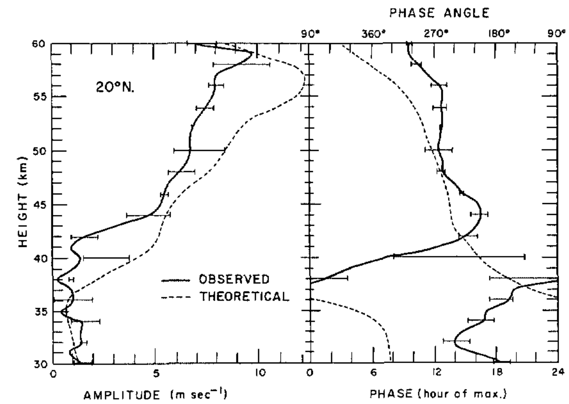

FIGURE 4.—Same as figure 1 for 20° N.

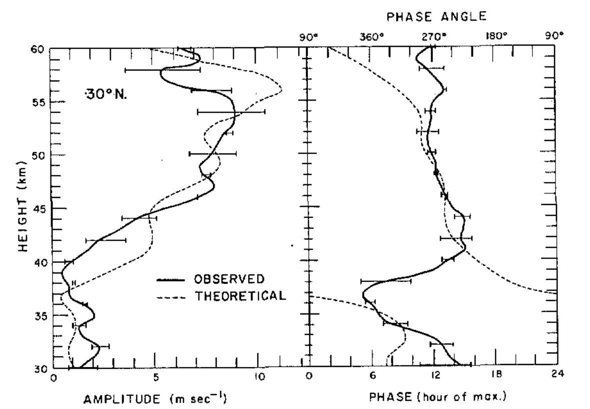

FIGURE 3.—Same as figure 1 for 30° N.

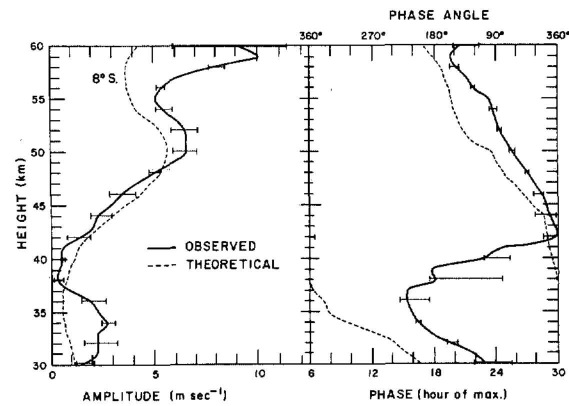

FIGURE 5.—Same as figure 1 for 8° S.

opposite phase behavior is even more pronounced than for the previous group.

8° S. (*Ascension Island*) Again, there is general agreement between theory and observation. The observed amplitudes are larger near 35 km and above 50 km. The phase differences noted for the previous two groups continue to apply. Theoretical phases are too early at high levels, and observed phases do not exhibit the rapid phase delay below 40 km given by theory. Because of the Southern Hemisphere location and the definition of phase as the hour of maximum south wind, phases differ by 12 hr from those of the low latitude Northern Hemisphere stations. The phase reversal would not appear if the phase were defined as the hour of maximum poleward velocity.

4. DISCUSSION

According to Lindzen's theory there are two primary drives for the diurnal tide: water vapor heating in the troposphere and ozone heating in the upper stratosphere and lower mesosphere. The solutions of Laplace's tidal equations for the latitudinal structure of the tide consist of two innumerable sets, one characterized by positive equivalent depths and one by negative. The positive equivalent depths are associated with propagating modes that transmit energy away from the region of excitation. The negative equivalent depths are connected with trapped modes in which the energy decays exponentially away from the region. Propagating modes are most readily activated at low latitudes and are inconsequential poleward of about 45° latitude. Trapped modes are most effective at high latitudes, but their influence also extends to lower latitudes.

The profiles in figure 1 for 61° N. are representative of trapped modes in which ozone heating is the principal drive. The phase is constant with height and the amplitude increases upward through the region of heating. Because of the decrease of air density with height, the wind amplitude increases to the top of the layer despite the energy decay.

The profiles for lower latitudes, for example those in figures 3 and 4, represent superpositions of propagating and trapped modes. Water vapor heating in the troposphere provides the main drive for the propagating modes. As before, ozone heating near the stratopause is mainly responsible for excitation of the trapped modes. The effect of superposition of the two types of modes is best seen in the theoretical phase profiles in which the phase changes rapidly with elevation except in the region between 45 and 55 km, where strong ozone heating excites the trapped modes.

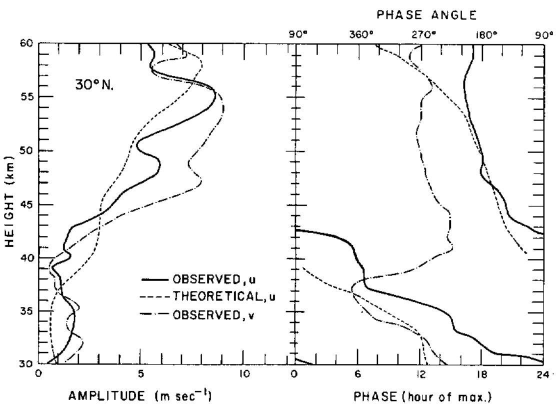

FIGURE 6.—Amplitude and phase of the diurnal variation of zonal wind component at 30° N. Data for meridional component are also shown; maximum (max.).

The fact that the observed phases change less rapidly than the theoretical in figures 3, 4, and 5 is an indication that the trapped modes are stronger relative to the propagating modes in actuality than in theory. Since the water vapor heating in the troposphere is almost certainly more accurately known than the ozone heating at high levels, the foregoing result suggests that a reexamination of the ozone heating is in order.

5. THE DIURNAL OSCILLATION OF THE ZONAL WIND COMPONENT AT 30° N.

As mentioned earlier, isolation of the zonal wind oscillation presents special difficulties because of the problem of trend removal. In summer, however, the trend is quite regular and can hopefully be eliminated by proper trend-fitting techniques. We report here the results of an initial attempt to measure the phase and amplitude of the zonal component for White Sands and Cape Kennedy, the stations with the most satisfactory wind data.

The first step in the analysis consisted of fitting seasonal trend curves to White Sands data, at 1-km intervals, for the months April–October 1964, 1965, and 1966. This was accomplished by fitting the sum of an annual cycle and its second, third, and fourth harmonics to the data by the method of least squares. Only observations taken within 2 hr of noon were used in making the fit. The trend curves for the three different years were so similar for the months of June, July, and August that it was decided to use only a single curve obtained by averaging the three and smoothing small irregularities. The differences between the actual observations for all hours (for the full record through August 1966) and the noontime trend curve were then harmonically analyzed in the manner of the meridional component to obtain the amplitude and phase of the diurnal variation.

The trend curve for Cape Kennedy was formed by determining differences between monthly average zonal winds at that station and White Sands and making appropriate interpolations. The monthly averages are given in Volume III, Nos. 6–8, Data Report, Meteorological Rocket Network Firings (Environmental Science Services Administration, 1964, 1967). The final harmonic analysis for the diurnal variation was made from the combined deviations of the winds at the two stations from their respective trend curves.

The results of the analysis are shown in figure 6. Also depicted are corresponding points from Lindzen's theory and the observed profiles for the meridional component. In agreement with theory, the zonal amplitude is generally smaller than the meridional and, except near 40 km, the phase difference between the two components is about 90°. At high levels, the observed phase remains constant, while the predicted phase becomes earlier. This behavior lends further support to the conclusion that the ozone heating is underestimated at these levels.

6. CONCLUDING REMARKS

From the present results, it would appear that Lindzen's theory has successfully predicted the major features of the tidal behavior in the 30–60-km region. Minor discrepancies have appeared that are almost certainly real. It appears likely that these differences can be removed by small adjustments in the relative roles of the water vapor heating and ozone heating. In particular, a reexamination of the ozone heating would appear to be warranted.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Richard S. Lindzen for providing comprehensive lists of the amplitudes and phases of the diurnal tidal motions as functions of latitude and height. The support of the National Science Foundation under grant GA-629X is gratefully acknowledged.

REFERENCES

Beyers, N. J., Miers, B. T., and Reed, R. J., "Diurnal Tidal Motions Near the Stratopause During 48 Hours at White Sands Missile Range," *Journal of Atmospheric Sciences*, Vol. 23, No. 3, May **1966**, pp. 325–333.

Environmental Science Services Administration, *Data Report, Meteorological Rocket Network Firings*, Vol. I, No. 1–Vol. IV, No. 4, U.S. Department of Commerce, World Data Center A, Asheville, N.C., Jan. **1964**–Apr. **1967**.

Lindzen, R. S., "Thermally Driven Diurnal Tide in the Atmosphere," *Quarterly Journal of the Royal Meteorological Society*, Vol. 93, No. 395, Jan. **1967**, pp. 18–42.

Meteorological Rocket Network Committee, *Data Report, Meteorological Rocket Network Firings*, Vols. I–XXVIII, U.S. Army Electronics Research and Development Activity, White Sands Missile Range, N. Mex., **1959**/60 winter–Dec. **1963** (available through Defense Documentation Center (DDC), DDC–IRA, Cameron Station, Alexandria, Va.).

Miers, B. T., "Wind Oscillations Between 30 and 60 Km Over White Sands Missile Range, New Mexico," *Journal of the Atmospheric Sciences*, Vol. 22, No. 4, July **1965**, pp. 382–387.

Reed, R. J., McKenzie, D. J., and Vyverberg, J. C., "Diurnal Tidal Motions Between 30 and 60 Kilometers in Summer," *Journal of the Atmospheric Sciences*, Vol. 23, No. 4, July **1966**, pp. 416–423.

[*Received September 3, 1968; revised October 4, 1968*]